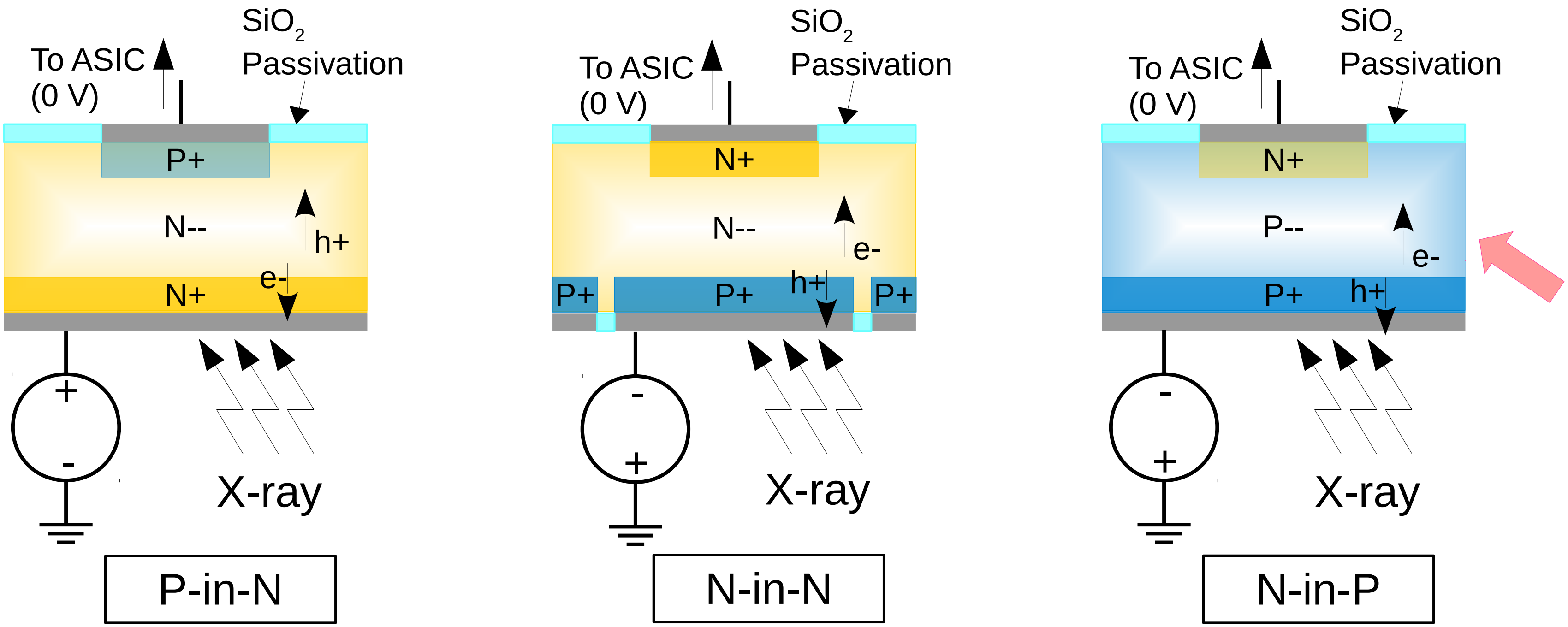
Guard Ring Optimization

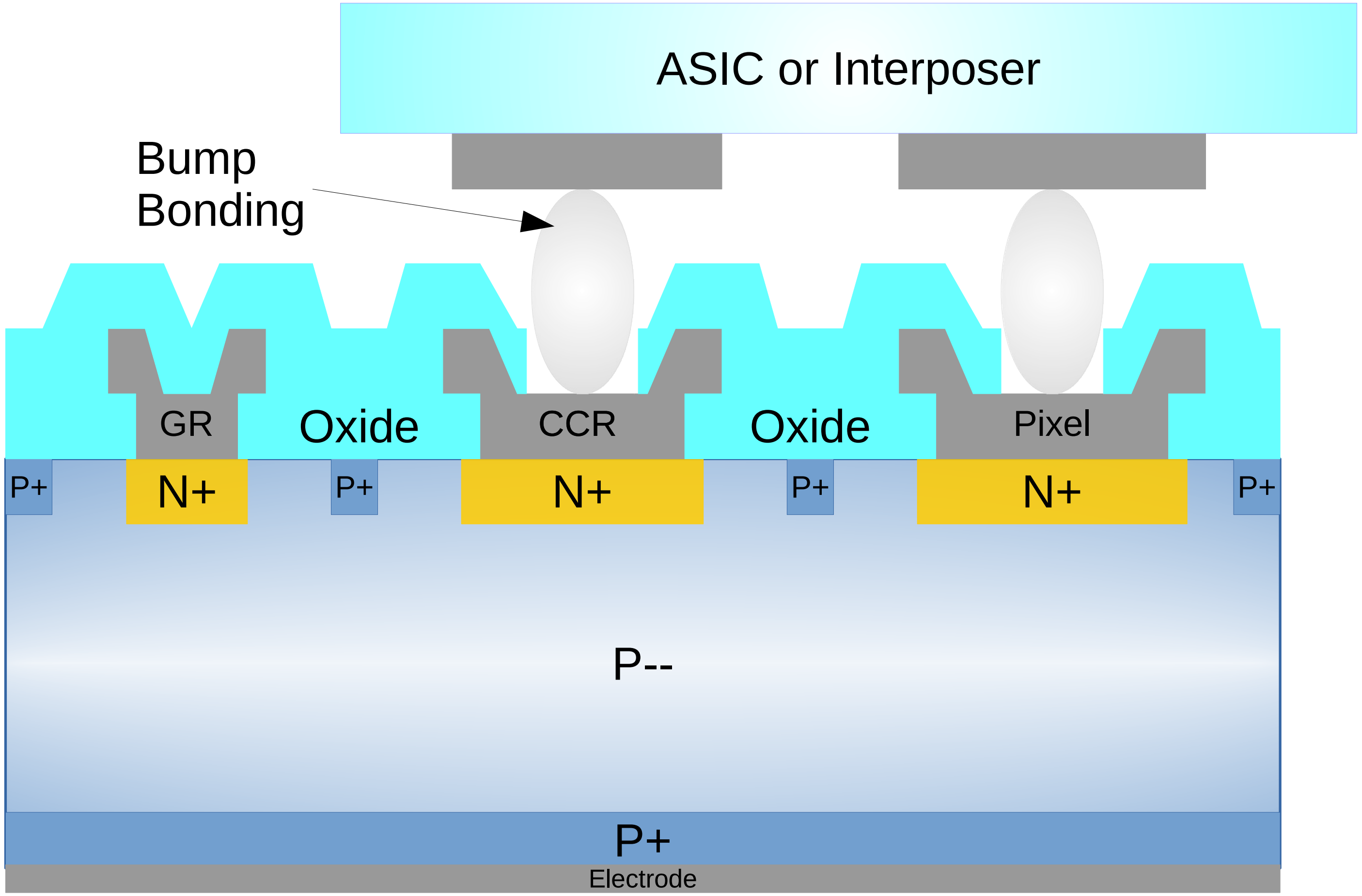
Taylor Shin

Silicon Diode Detectors

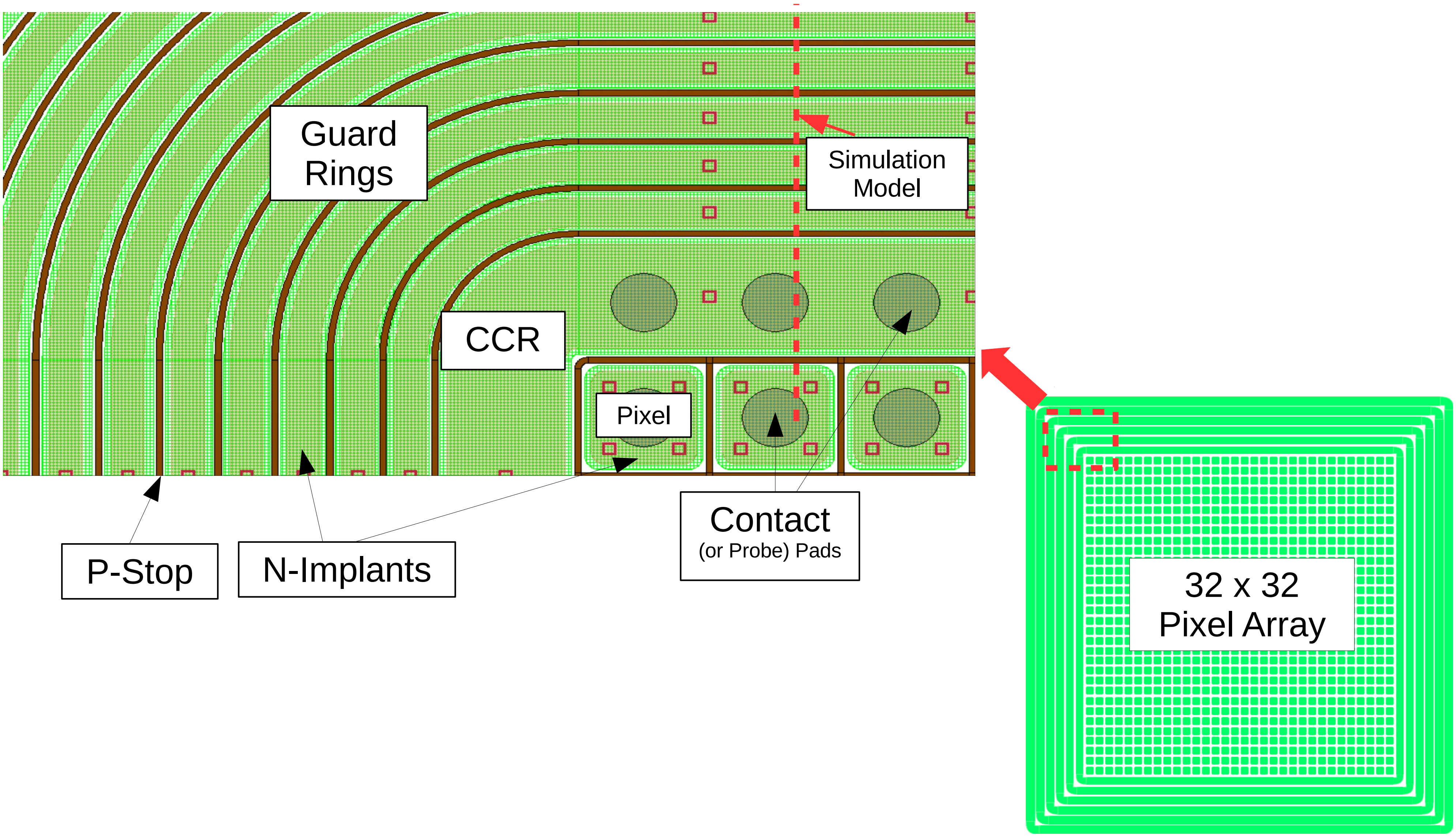


- Three types X-ray to electron-hole pair converters.
- P-in-N: Most widespread technology so far due to simplicity and affordable substrate from FZ process. However, uses holes as a main signal carrier and the substrate type changes after lots of radiation.
- N-in-N: Faster than P-in-N since electron is a major signal carrier. But requires double side process to implement guard rings (The depletion region stretches from the back electrode rather than from pixels) and also vulnerable to type inversion after prolonged radiation. Once type inversion happens, the electric field stretch from N+(pixels.) So, we need guard rings at both sides. → So complex to manufacture. (note that process difficulty jumps with mask numbers, exponentially.)
- **N-in-P**: Fast. Also much stronger (in terms of radiation hardness) since the substrate is already P-type. The P-type substrate supply was problematic but the issue has been solved.

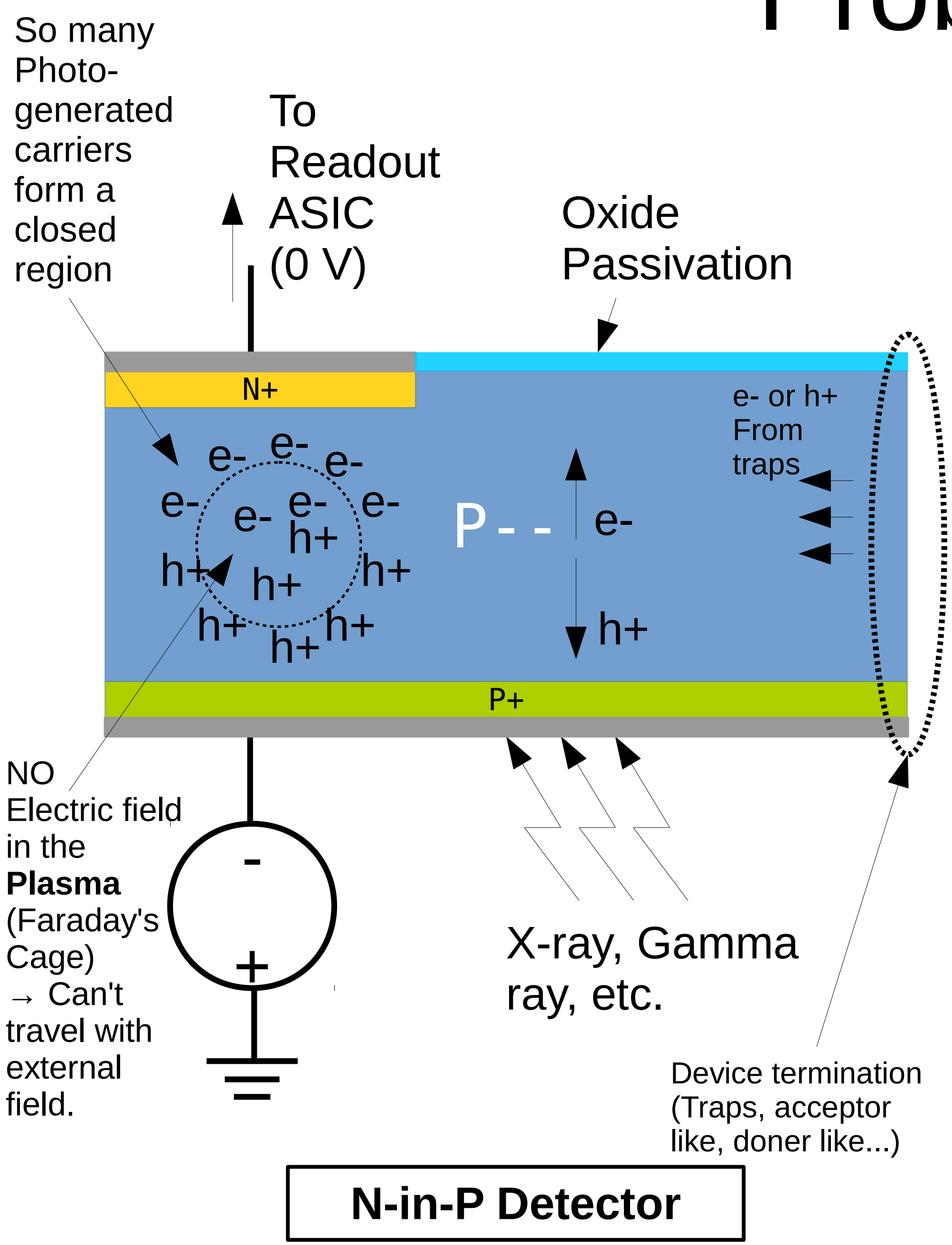
N-in-P Prototype Structure



Mask View of the FASPAX 15 GR Sample

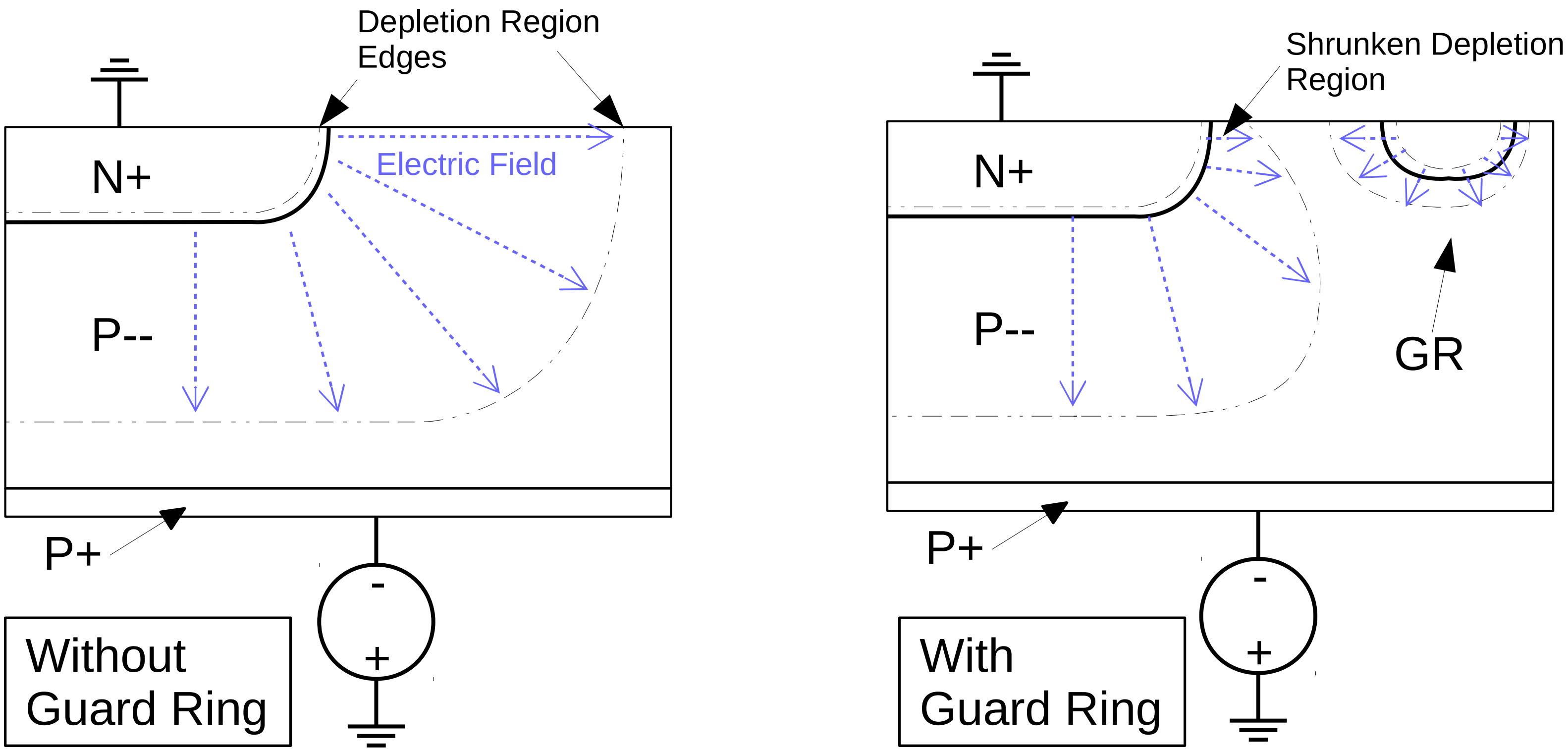


Problem



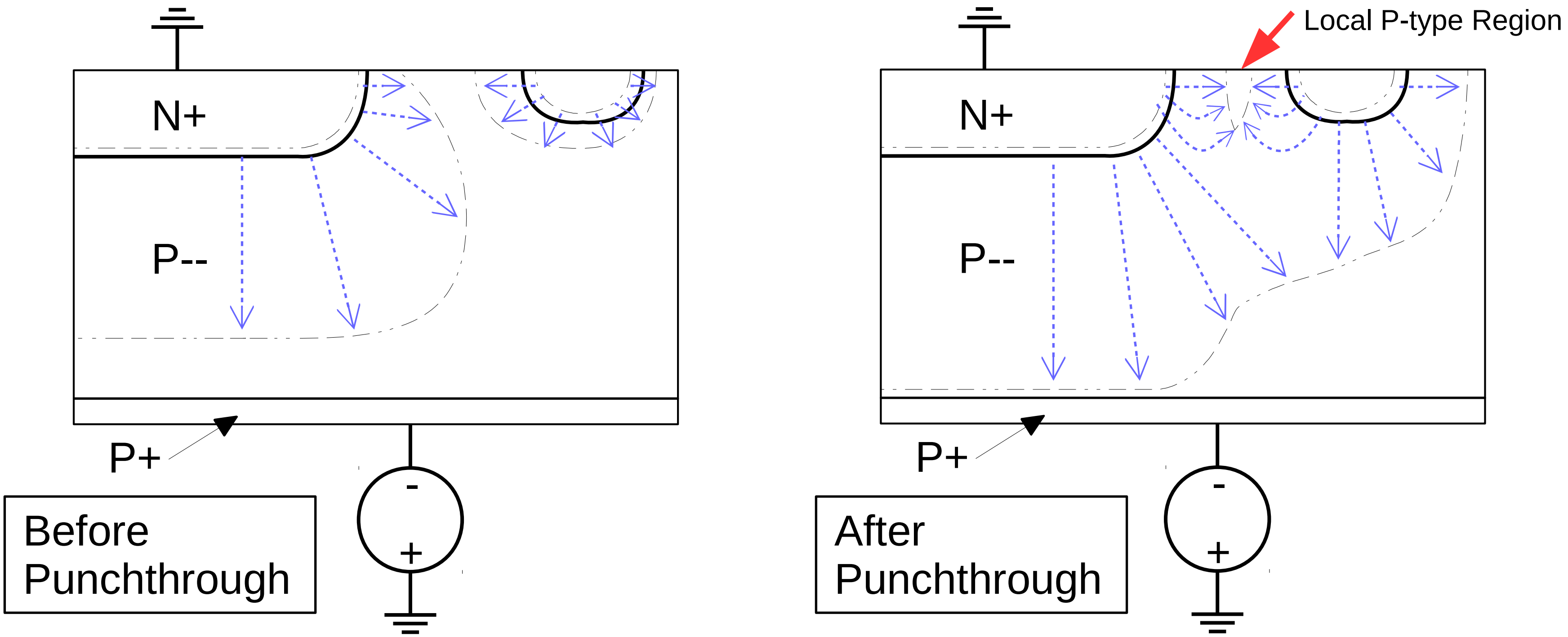
- Problem: the upgraded beamlines emit too many photons per bunch → causing Plasma Delay Effect
- To avoid such unexpected delay, we need to apply extremely high bias (~ 900 V?) across the silicon detector.
- Such high bias causes additional charge injection from device termination. → Additional noise
- Furthermore, we can't control trap density at wafer termination.
- Thus, we need to reduce or eliminate bias at the vicinity of device termination.

The Guard Rings



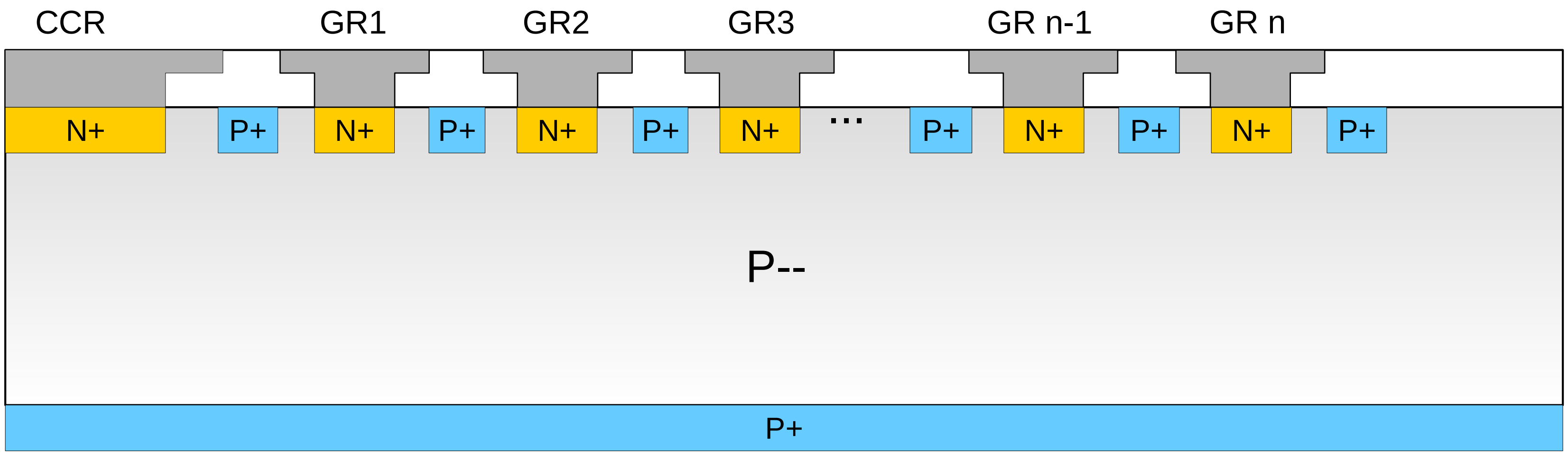
- Manipulates electric field to prevent it reaching the device termination.
- Commonly used in power electronics.
- Currently, FASPAX project employs floating guard rings which are most convenient to implement. (just drop some implants with contacts)
- The implanted fixed charges disrupt the electric field from the pixel (or current collection ring) electrode.)

The Punchthrough



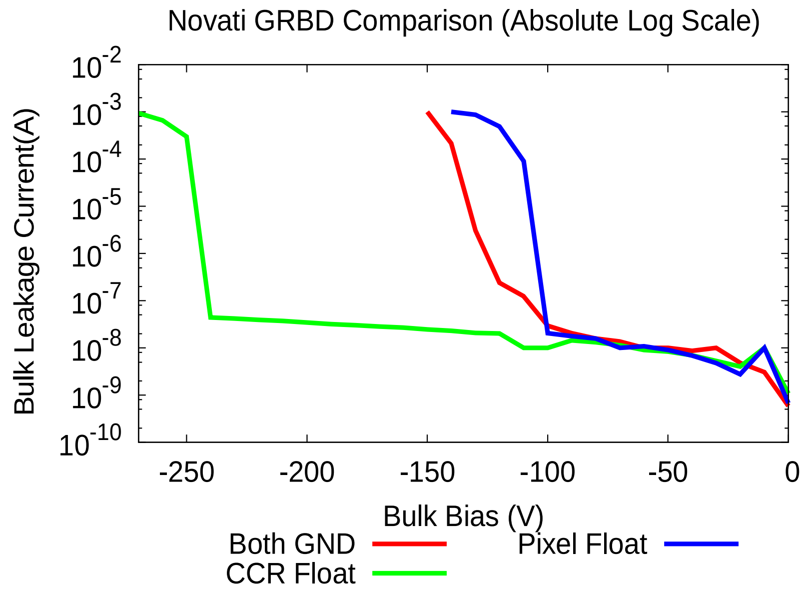
- In fact, the reverse bias is too high… Of course, we need a fully depleted bulk to ensure ehp collection.
- Also, we need even higher substrate bias to avoid the plasma delay effect.
- In this case, the electric field from the pixel electrode (grounded electrode) extends over the guard rings.
- Such extension leads to a localized p-type region which attracts electric field → concentrates the electric field → a lot of potential drop within the short region.
- The right side of the local p-type region should increase potential back… but it seems the intensity of electric field is not enough.
- In FASPAX, we rather implemented the local p-type region as a p-stop implants. Thus, every single bit of potential drop happens at the p-stop vicinity.

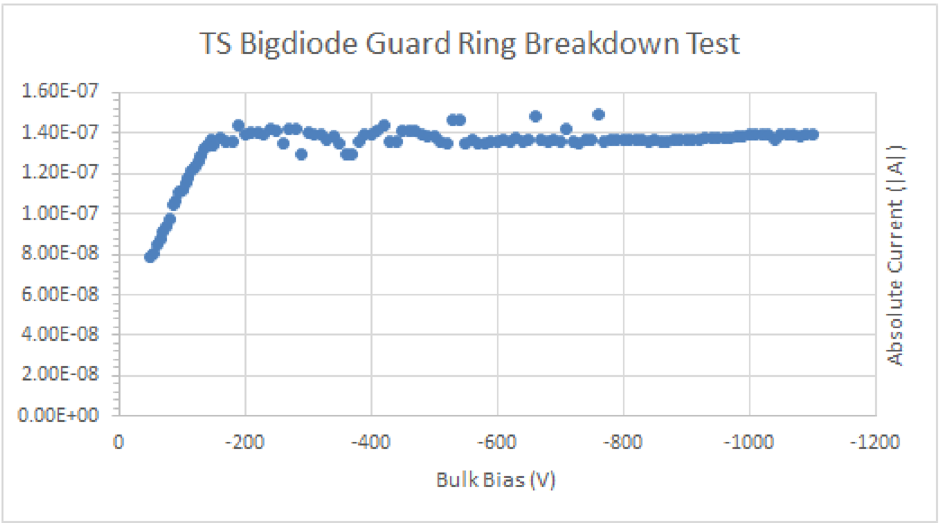
FASPAX Guard Ring Structure



- Two variants: 8 guard rings or 15.
- Measurement has been performed on test samples has shown that the breakdown (~ -135 V of V bulk.) is actually happening earlier than expectation.
- We suspected the breakdown is actually happening somewhere at the guard ring surface.

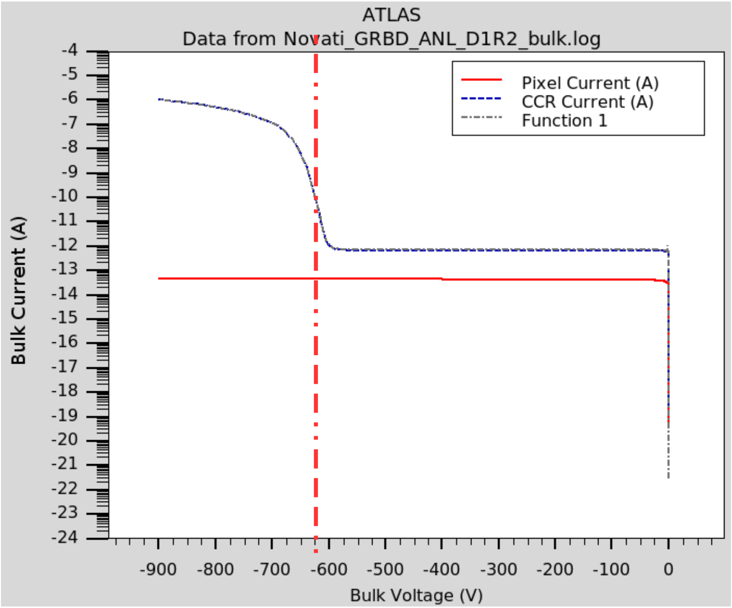
I-V Sweep Results

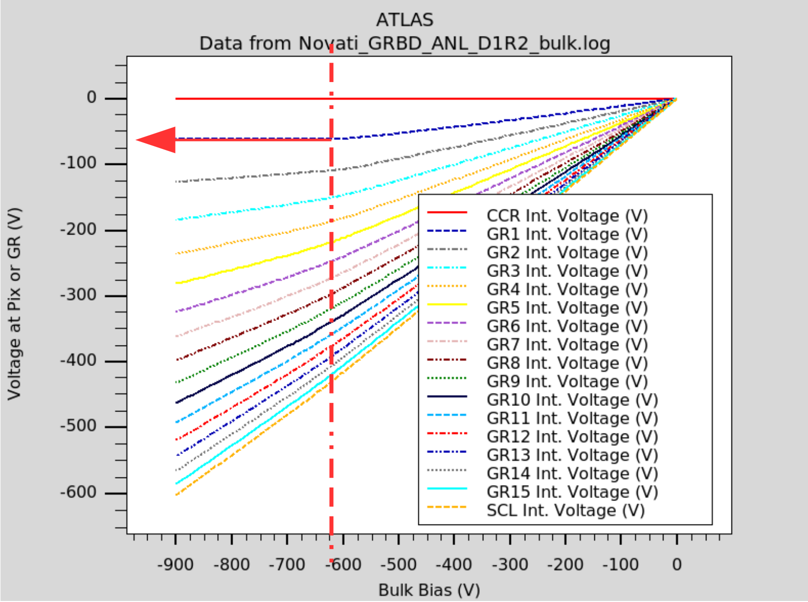




- Upper Figure – FASPAX 15 GR p-stop sample.
  - Breaking down at (as low as) ~ -135 V of bias
  - CCR Float: CCR became a guard ring → improved by twice but not enough.
  - We have taken the data from 16th row pixel.
- Lower Figure – FNAL Device with 5 mm-wide, p-stop sample.
  - Two external biased guard ring design. (Similar to Hammamatsu photodiode they were working on.)
  - Also breaking down as low as -200 V.
  - The graph is kind of misleading with the leakage current of 0.1 uA. But, in fact, we had some problem with compliance setting at the characterization system. (One reason why we ordered Keithley 4200.)
  - The voltage bias was actually limited to -185 V due to misleading (1/1000) compliance setting.

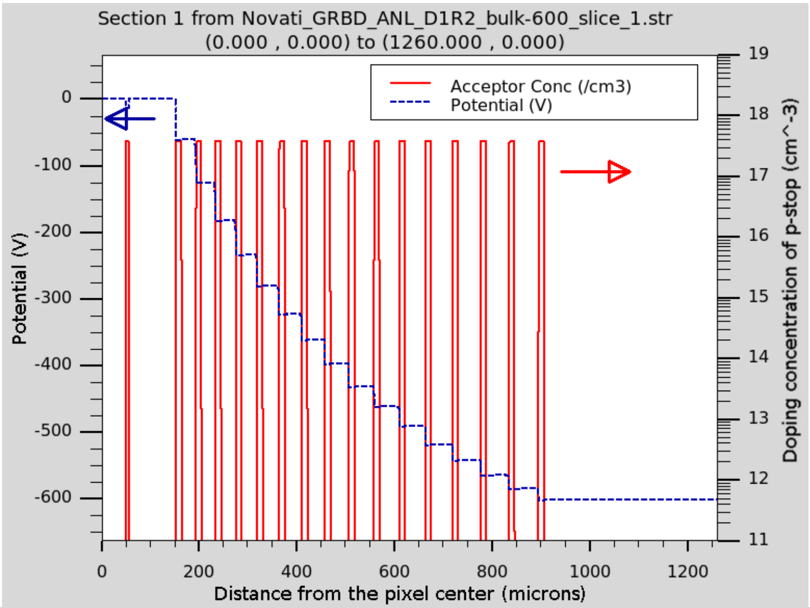
Simulation Result
(I-V, Potential)

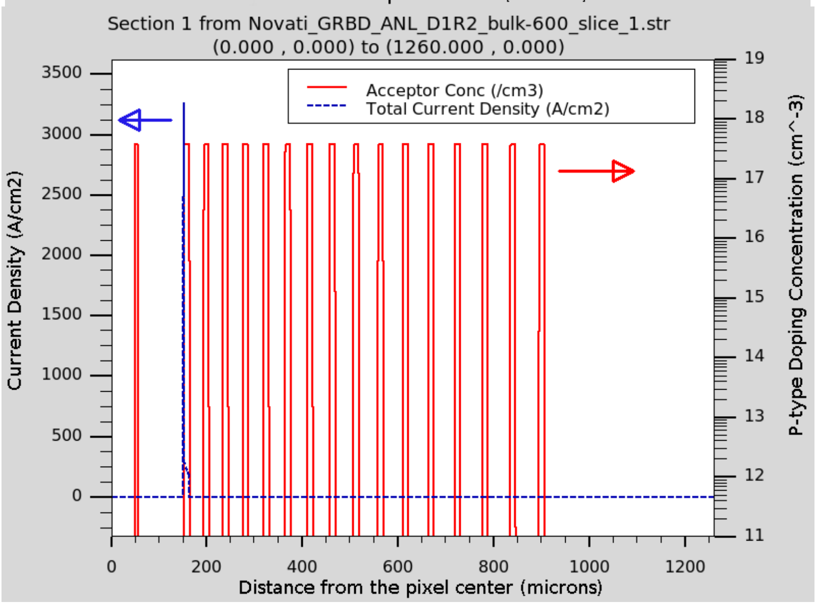




- Breakdown at -630 V.
- Much higher than expected due to lack of trap state implementation in SiO_2.
- Also, the bulk silicon was truly intrinsic.
- Interface trap (Q_{ss}) was 8.8 x 10^{11} /cm^2. (sheet)
- The Potential of the first guard ring is at -63 V.
- The last floating guard ring potential is staying at -460 V when the bulk bias was -630 (breakdown point.)
  - 170 V bias across the detector at the termination.
  - Depletion region reached here.
  - Of course, not good...

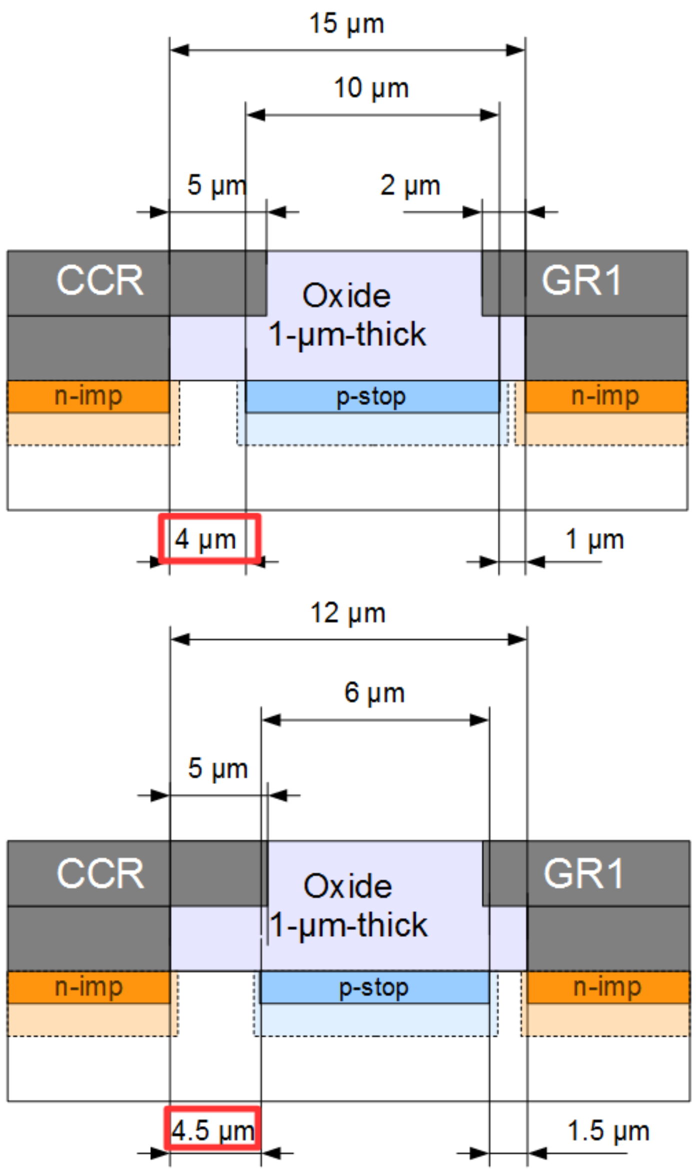
Simulated Breakdown
(Potential, Breakdown Current)





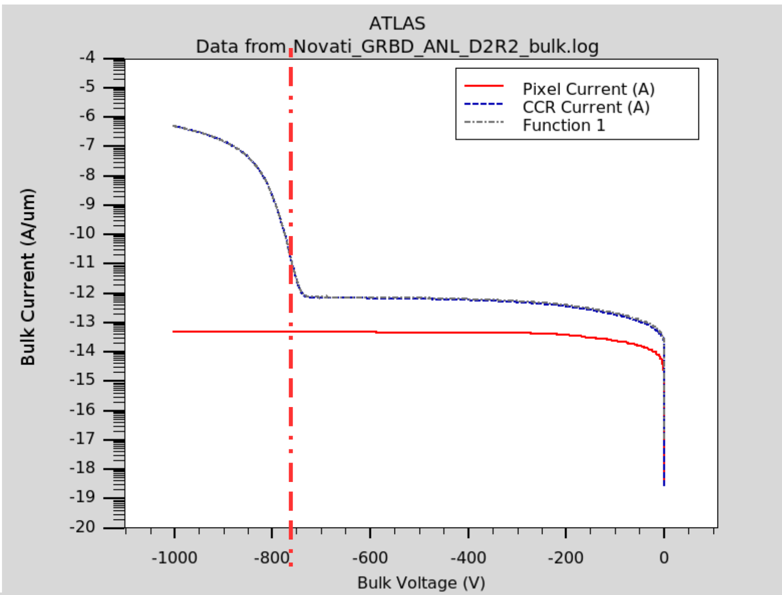
- The potential drop per each guard ring decreases.
  - Optimal design can be achieved when all the potential drop equalizes.
- Obviously, the first p-stop implant breaks down.
  - Its vicinity is actually, N- i-P diode under reverse bias.
  - In fact, if the second p-stop does not break, 2^{nd} p-stop GR breaks.

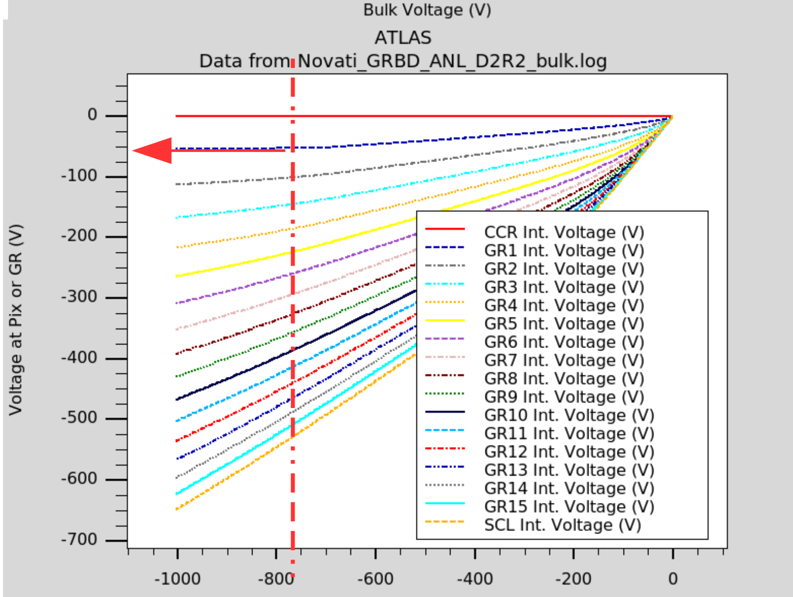
Shorter P-stop Width
(10 → 6 um)



- One way or another, we need to fix the problem.
- Fundamentally, we can reduce doping concentration (either N+ or P-stop) but we don't have direct control on the process.
- Another alternative can be giving more distance from N+ contact to reduce electric field.
- By compromising the design constraints, we reduced the 10-um-wide p-stop implant to 6 um. → Obtained 0.5 um more space.
- The 6 um design was submitted for next run. Suspected to be received in next March.

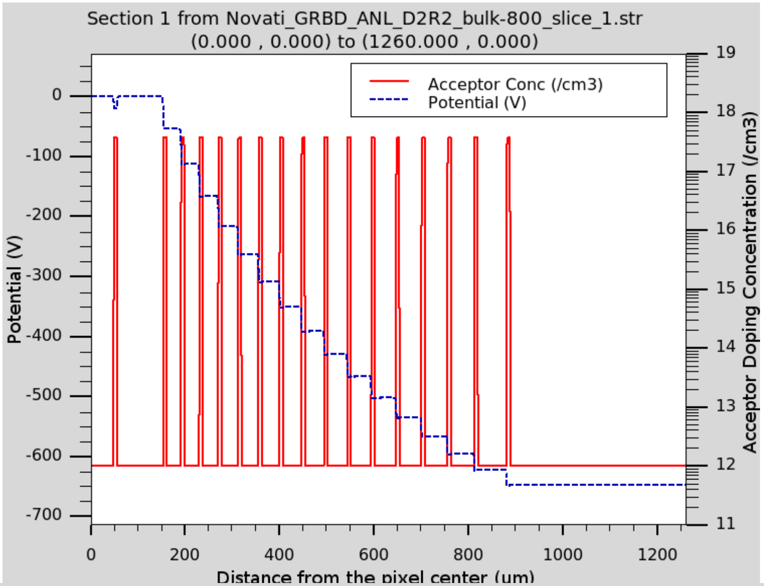
2^{nd} Design
(I-V, Potential)

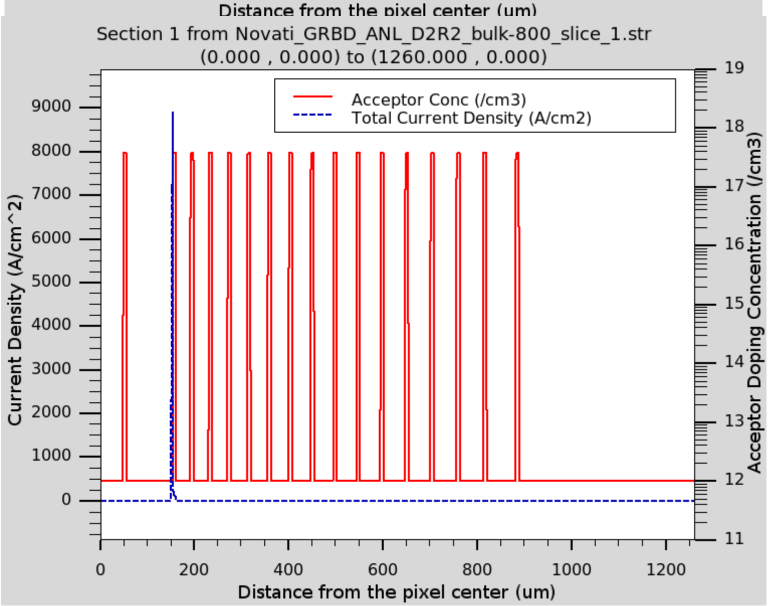




- The breakdown point advanced a little bit: (-630 → -750)
  - In fact, if the substrate doping was intrinsic, it breaks down at -1200 V.
  - The first guard ring breaks down at -60 V as well. However it breaks down at -80 V without substrate doping.
- Yet, the potential drop was not enough: -570 V at the last guard ring at the breakdown bias.
  - The publication (IEEE 2015 NSS-MIC Proceeding) has data from intrinsic substrate.
  - The simulation on 10 um case with proper substrate doping is underway.

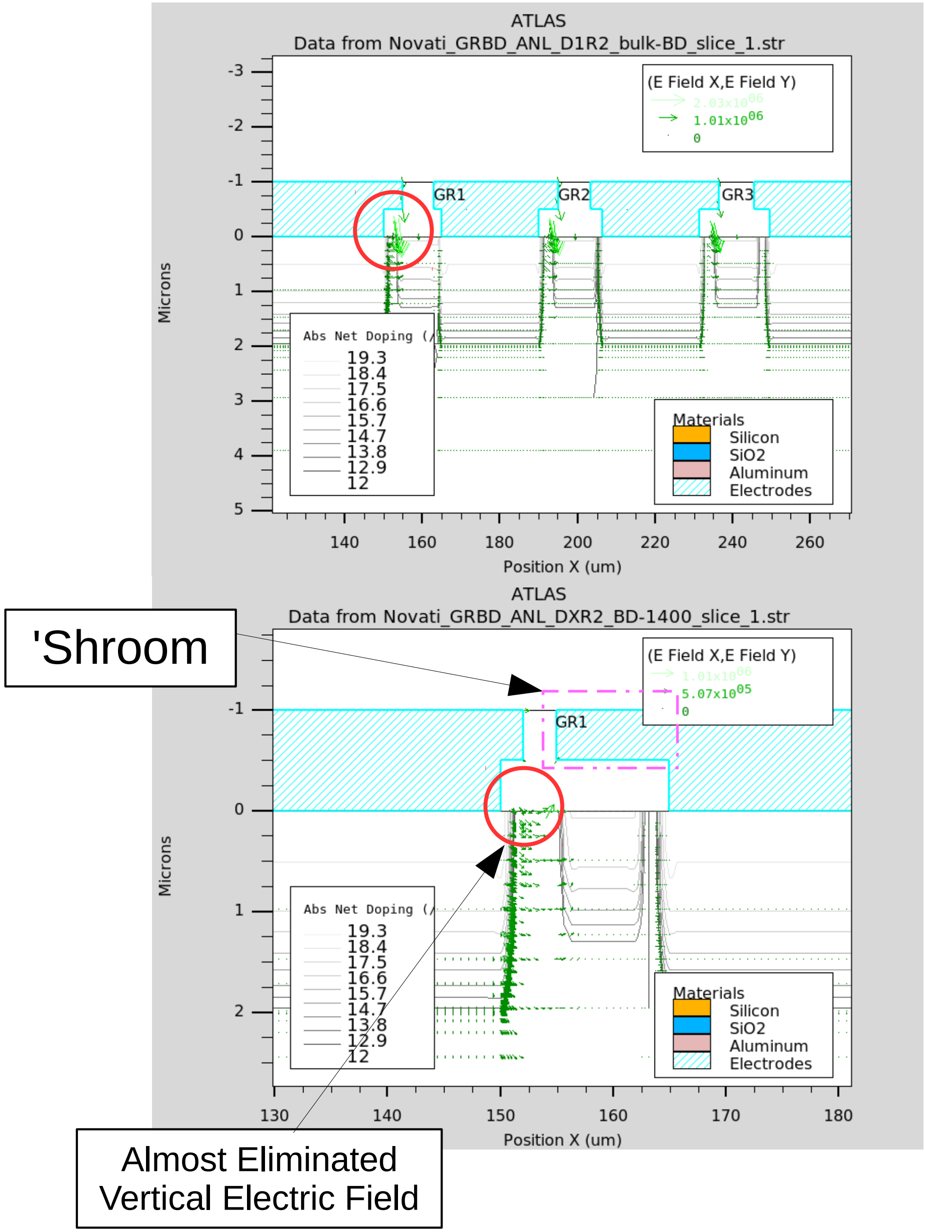
2^{nd} Design
(Potential, Breakdown Current)





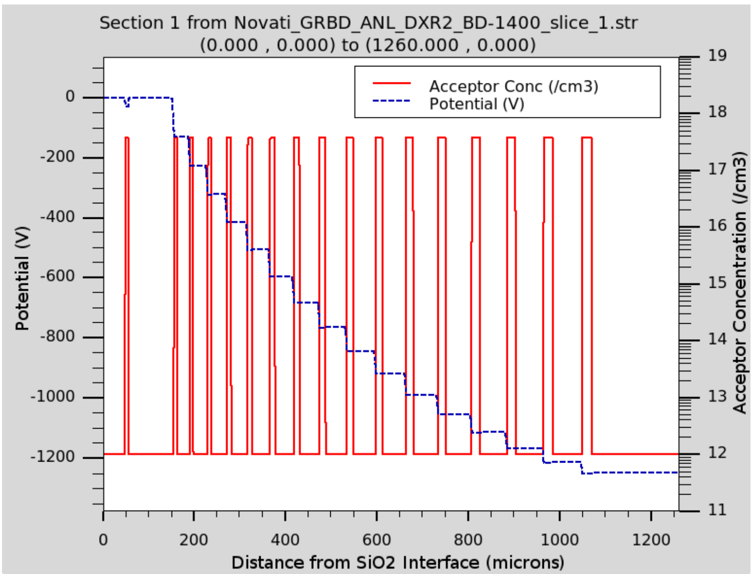
- Potential drop profile seems to be a bit more optimized.
  - The potential drop at each guard ring seems to be more uniform.
- Again, the breakdown actually happened at the first guard ring.
- The breakdown voltage has been improved a bit… but we still need a fundamental solution!!

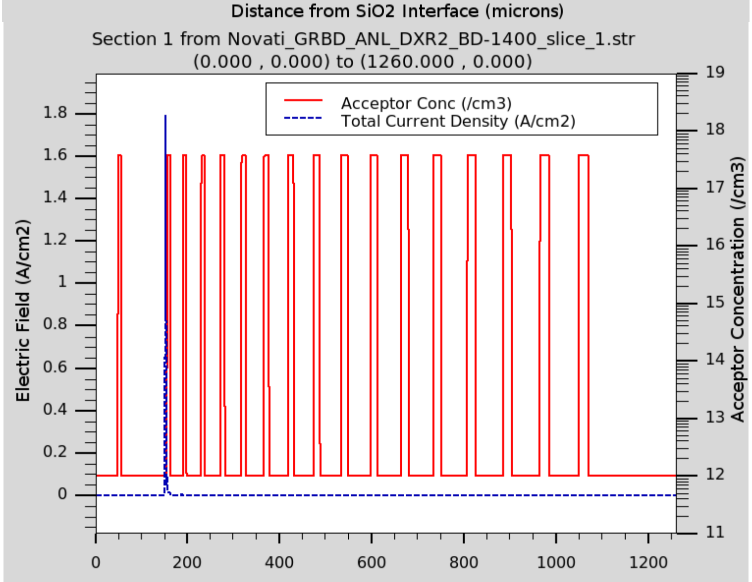
3rd Design ('Shroom?)



- Sounds weird, but the overhang from previous (or left) electrode overlapping p-stop causes tons of electric field.
- Mainly, it is vertical direction and doesn't seem to be significant to the reverse biased N-i-P vicinity.
- However, O. Koybasi, et al. pointed out that the vertical electric field can be a menace.
- So, we decided to move the p-stop towards to next n+ implant and extended guard ring overhang → ('Shroom)
  - In fact, they point out that the 'Shroom doesn't need to be too long. So we stayed at 9 um-long to cover the entire 6 um-wide p-stop implant.

3rd Design
(Potential, Breakdown Current)

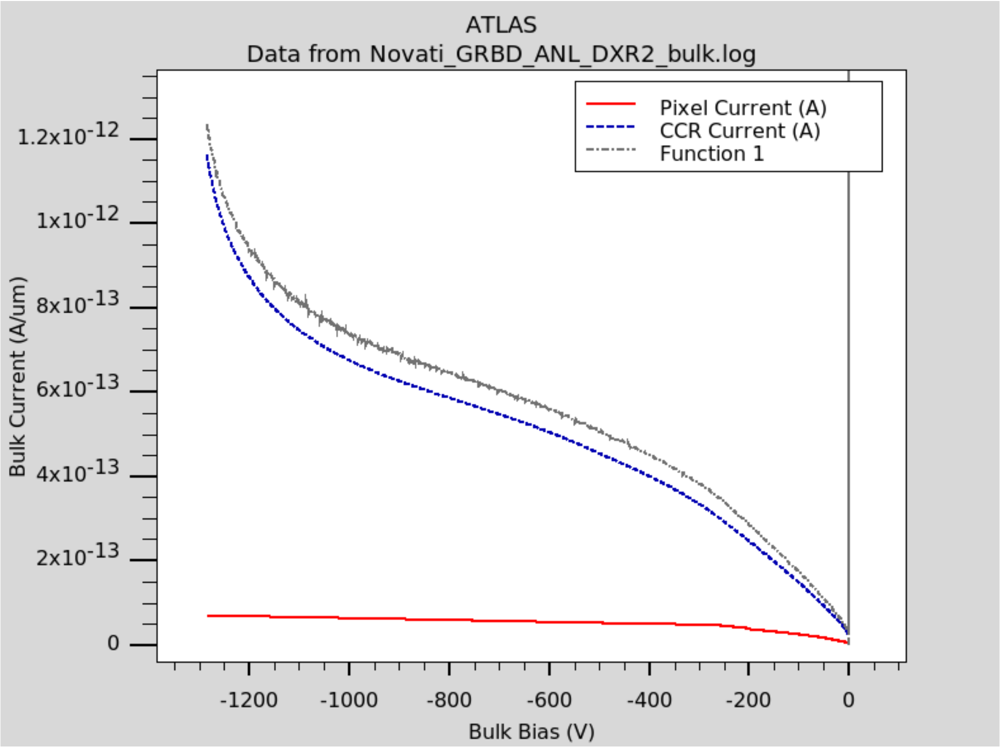


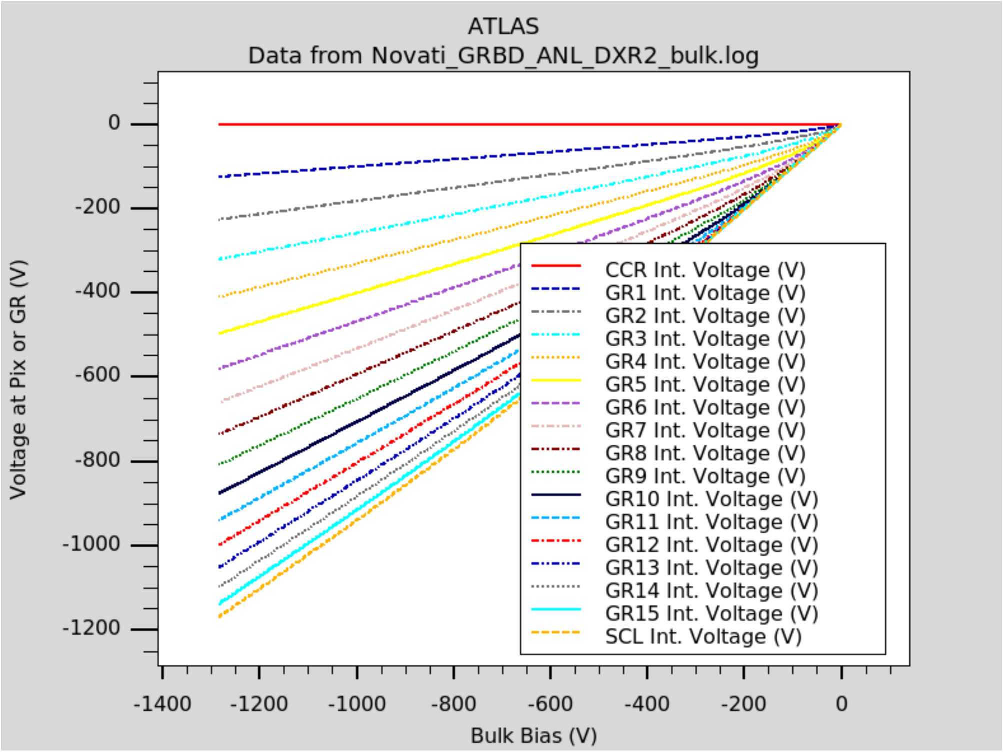


- It breaks down at the first guard ring.
- The first guard ring sustains up to -120 V of bias which is technically doubled from previous design.
- The breakdown actually happened at -1250 V of bulk bias.
- Also, the last guard potential is as low a which ensures almo across the wafer ter

- So, **I guess we nailed it!!**

I-V Characteristic and potential from the 3rd device

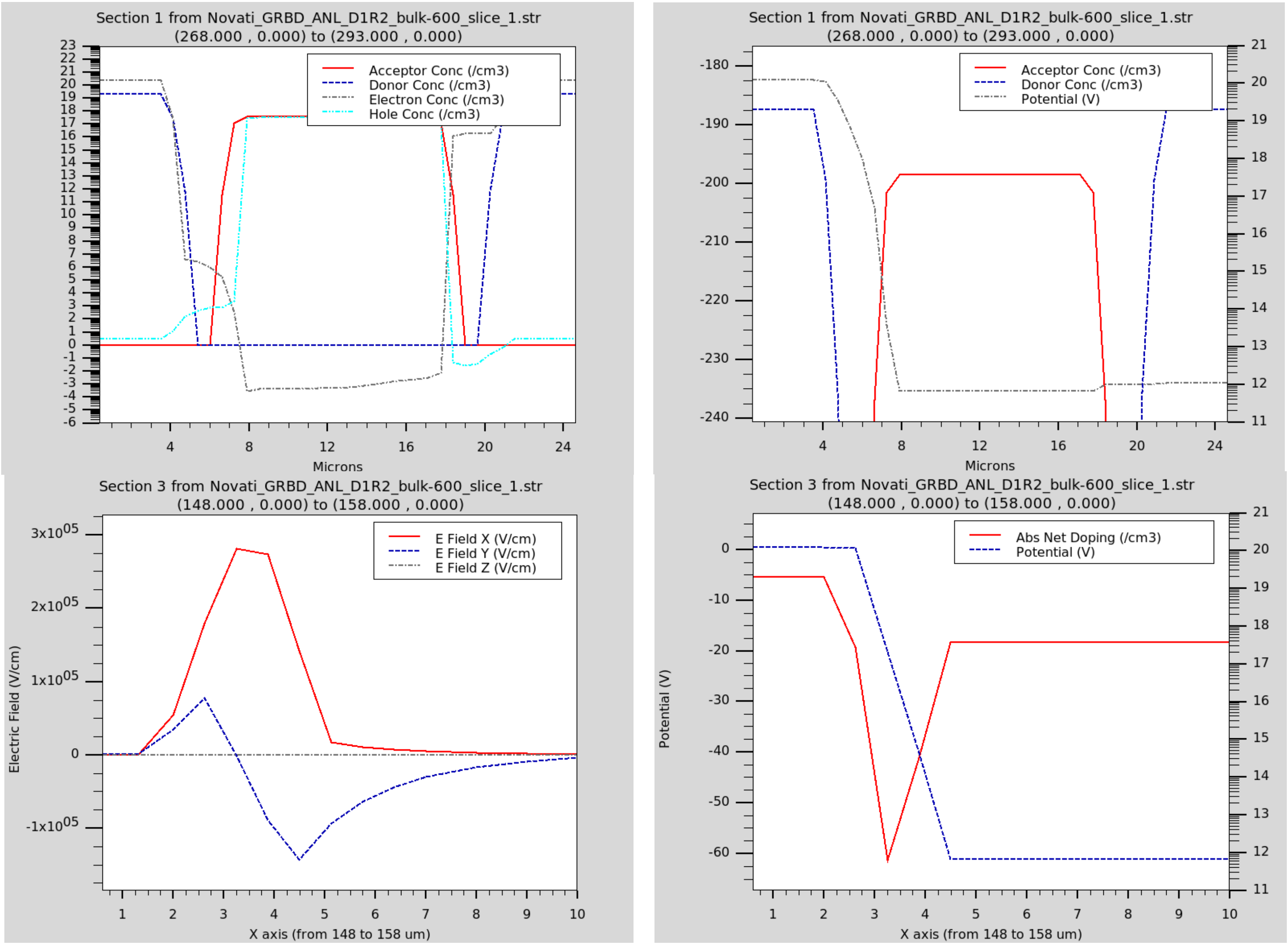




Conclusions

- Unexpectedly, suppressing vertical electrical field resulted a substantial improvement.
  - Not to mention that the distance from N-implant was extended when we moved p-stop implant: pushed down the breakdown point even further.
- However, we need to actually implement and verify improved breakdown bias condition.
- According to Nov. 30th meeting, Novati will reduce p-stop doping concentration which expected to improve breakdown strength even further.

Zoomed in Figures
(E-field and potential)



Additional Figures